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Simulation and Analysis of Electric Control System for Metal Halide High Intensity Discharge Lamps

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***Abstract*— Metal Halide HID lamps are becoming popular because of its high efficacy. The operating characteristic of Metal Halide (MH) HID lamps is complex as it has several stage of operation. The objective of this paper is to design an electric control system for metal halide high intensity discharge (HID) lamps using half bridge inverter. The LCC resonant mode is used to provide the sufficient voltage and current to the MH lamp during its ignition and normal running condition. An adaptive control method is used to regulate the lamp power. A close loop current control method is used. In this close loop Type-3 regulator is used as a compensator. The variation in lamp power with and without loop is discussed. The stability of the close loop is also analysed. PSIM Simulation Software is used to do this analysis.**

***Index Terms*— Metal Halide Lamp, Half bridge Inverter, LCC Resonant Tank, Type-3 Regulator, PSIM.**

I. Introduction

Metal halide HID lamps are appropriate for many application due to its long life and high luminous efficacy [1]-[2]. Since MH lamps have the characteristics of negative incremental impedance, electric control system is required to stabilize the lamp current. With the fast development in power electronics, electric control system for metal halide HID lamps has replaced largely the traditional magnetic control system. Electric Control System provides the reduction in size of the control system and improved quality performance [3]-[5]. Due to the aging effect the internal impedance of lamp is varied which results in change in power of the MH lamp as it becomes older [6]. This phenomenon may increase the lamp power above its rated value during normal operating condition and may create safety issues at the installation.
Moreover, the complex MH lamp behaviour also increases the complexity of the control circuit because these lamps have different operating phases, which can be classified as follows.
a) Lamp starting—the lamp has very high impedance before ignition and a pulse of approximately 3 kV is necessary to start a cold lamp.
b) Lamp heating—the heating process takes from tens of seconds to minutes. The lamp starts presenting small impedance that increases as long as the lamp is warmed up. This stage must be as short as possible in order to avoid the detrimental effect of the glow current.
c) Steady state—after the lamp heating, the lamp reaches the steady state and parameters like (lamp power or current) must be controlled.The half bridge inverter along with LCC resonant tank is widely used because it

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does not require any additional igniting circuit [7]-[9].
In this paper half bridge inverter and LCC resonant tank is designed and used with closed current loop to maintain the lamp power. Type-3 Regulator is used to stabilize the overall performance of feedback loop. Figure-1 shows the block diagram of electrical control system. As shown in the figure inductor current from LCC resonant tank is sensed and is given to Type-3 Regulator which controls the duty cycle of the square

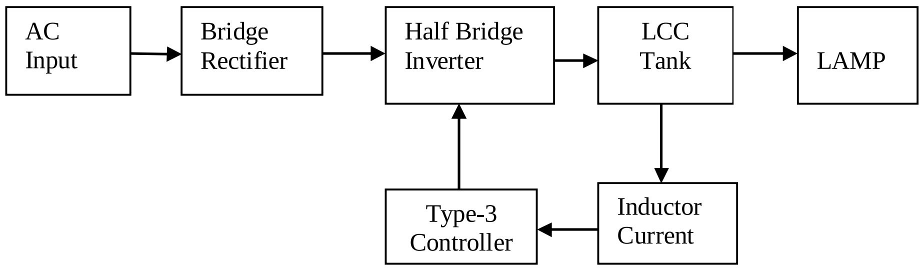


Fig.1 Block Diagram of Control System for M.H lamp

wave that is given to half bridge inverter switches. The duty cycle of square wave is changing according to the load variation, this scheme is referred as Pulse Width Modulation (PWM). The lamp is operated at the rated power by regulating the switches of half bridge inverter. The LCC resonant tank is designed for driving a 60W MH lamp and simulation results are analysed. Satisfactory performance is obtained from the simulation result.
This paper is organized as follows. Working of electric control system is shown in Section II. Section III shows the design procedure of LCC tank for M.H lamp. The control strategy (closed current loop) and stability analysis are presented in Section IV. Simulated circuit and Experimental results are shown in Section V.

II. ELECTRIC CONTROL SYSTEM CONFIGURATION AND OPERATION

In this section, the behaviour of open loop electric control system is analyzed, as shown in Fig.2. The resonant tank consists of C_s, L and C_p. Resistor R_{lamp} represents the equivalent resistance of MH lamp. To analyse the steady state or normal running circuit behaviour, the following assumptions are made: (1) Switches and diodes are ideal. (2) Reactive elements of the resonant tank are ideal. (3) In steady state, $R_{lamp} << 1/\omega C_p$, the capacitor C_p can be neglected and the resonant tank is working as a series resonant tank. (4) The operational frequency is greater than the resonant frequency. A switch cycle can be divided into four modes and main
waveforms of the electric control system are shown in Fig.3.In Fig.3, V_{g1} and V_{g2} represent the driving signal of S1 and S2 respectively. V_{ds1} and V_{ds2} show the on off time of switch S_1 and S_2.

A. Mode I ($t_0 < t < t_1$)

At t_0, switch S_2 is turned off. The current shifts from S_2 to D_1, because the resonant tank is inductive and the current through the inductor is negative.

B. Mode II ($t_1 < t < t_2$)

At t_1, S_1 is turned on however no current goes through it until the current through the inductor becomes positive. So S_1 is ZVS switch. After the current through the inductor is positive, the resonant tank begins to draw energy from input source, the capacitor Cs is charged and the energy stored in it increases.

C. Mode III ($t_2 < t < t_3$)

At t_2 switch S_1 is turned off and D_2 is turned on. The current through the inductor shifts from S_1 to D_2, because the resonant tank is inductive and the current through the inductor is positive.

D. Mode IV ($t_3 < t < t_0$)

At t_3, S_2 is turned on, however no current goes through it until the current through the inductor becomes negative. So S_2 is ZVS switch. During the interval [t_3, t0] the resonant tank begins to provide energy to load R_L, here t_0 is the starting point in next period alike.

At t_0, S_2 is turned off, D_1 is turned on. After this time the circuit repeat above the stages.

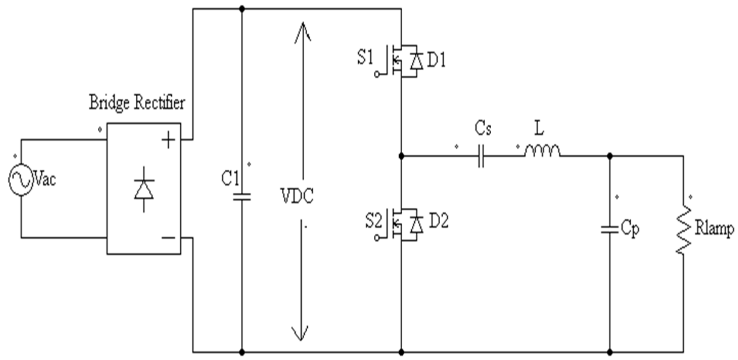


Fig.2 Circuit Diagram of Open Loop Electric Control System

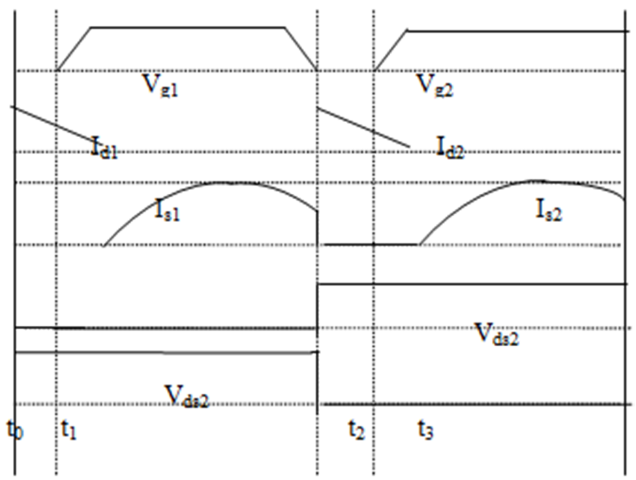


Fig.3 The key waveforms of Open Loop Electric Control System

III. DESIGN CONSIDERATION

The following specifications have been used in the design-
(a)Input Voltage 220V dc (b) Load 60 W MH lamp (c) The equivalent resistance Rlamp is like as the following R_{lamp}=1000KΩ before the lamp is ignited. R_{lamp}=80Ω if they operate in steady state. (d) Output Voltage V_{out}=3200V and 135V at ignition and normal running condition respectively. (e) Maximum operation frequency (f_{max}): f_{max}<550 KHz, minimum operation frequency (f_{min}): f_{min}>100 KHz to avoid the acoustic resonance. Following steps should be followed in designing the LCC resonant Inverter-

A. Capacitive Ratio (C_n)

$$C_n=\frac{C_p}{C_s} \tag{1}$$

In designing of electric control system for MH lamps, capacitive ratio (C_n) should be in the range of 1/10-1/30. In this design C_n=1/20 is selected i.e. C_s=12nf and C_p=0.6nf.
B. In ignition mode resonant inverter acts as a parallel resonant inverter while in steady state phase the resonant tank is working as a series resonant tank. The equivalent resonant frequency f_o can be calculated by-

$$f_o= 1/2\pi\sqrt{LC_s} \tag{2}$$

If minimum operational frequency f >f_o, then the input impedance of the resonant tank has an inductive characteristic and the switches in the inverter are ZVS switches. In this design f_o=245KHz and we take f=450Khz.

C. Calculation of voltage gain

The r.m.s voltage of input voltage V_{in} (V)

$$V_{in} = (4*V_{DC})/(\pi * \mathrm{sqrt}(2) *2) \quad (3)$$

In this design V_{DC} =220V and V_{in}=99.08V.The r.m.s voltage of the lamp (V).

$$V_{out} = 135/\mathrm{sqrt}(2) \quad \text{In Steady state} \quad \} \quad (4)$$
$$= 3200/\ \mathrm{sqrt}(2) \quad \text{In Ignition State} \quad \}$$

The voltage gain M is:

M = 0.96 In steady state

= 22.8 In Ignition State

TABLE.I : PARAMETER OF ELECTRIC CONTROL SYSTEM

Input Voltage V_{DC}	220V
Lamp Voltage V_{out}	135V
Lamp Current I_{out}	0.52A
Lamp Power P_{out}	60Watt
Series Inductance L_s	35µH
Series Capacitance C_s	12nF
Parallel Capacitance C_p	0.7nF
Lamp Resistance R_{lamp}	80Ω

At f=f_o or f/f_o= 1, voltage gain is maximum and this voltage gain is called quality factor Q.

D. Calculate Characteristic Impedance (Z_o): $Z_0 = R_L/Q$ (6)

and $Q = V_{out}/V_{in}$ when f/f_0 = 1. if Land C are known then

$$Z_0=\sqrt{\frac{L}{C_{eq}}} \quad (7)$$

where $C_{eq} = \frac{C_s.C_P}{C_s+C_p}$

E. If L and C_s are unknown, then

$$L=\frac{Z_o}{2\pi f} \quad (8)$$

and

$$C_s=\frac{1}{2\pi Z_o f} \quad (9)$$

In this design Q=0.74 and f = 450 KHz, so the design results are L=35uH, C_s=12nf and C_p=0.7nf.Table I shows the design parameter of Electric Control System.

IV. CONTROL STRATEGY AND STABILITY ANALYSIS

The deterioration of the gas, contained in the discharge tube, decreases the number of free electrons and thus increases the lamp resistance. The equivalent lamp resistance may increase more than 100% of the original value during aging. In case of open loop lamp power changes drastically, therefore the close current loop is necessary to compensate the increment of lamp equivalent resistance [10]. The inductor current is sensed then it is given to Type-3 Regulator. The output of Type-3 Regulator is connected to non inverting terminal of op-amp comparator, while inverting terminal of op-amp comparator is connected to triangular wave source of high frequency. The frequency of triangular wave is adjusted according to voltage required to the lamp. At ignition stage frequency of triangular wave is high comparison to steady state. This phenomena is called

frequency sweeping. In this design ignition frequency is 540 KHz while steady state frequency is 450 KHz. Moreover the comparator produces the output in the form of square wave and the frequency of square wave is changing according to lamp resistance variation. This scheme is referred as Pulse Width Modulation (P.W.M) switching control. In this way we can get a constant power across the lamp in spite of load variations. From Section V one can easily understand about the generation of P.W.M wave as shown in Fig.6.

A. Design Procedure of Type-3 Regulator

Determine the transfer function (Bode Plot) of the modulator or control system.
Choose the overall gain crossover frequency and desired phase margin.
Synthesize or design a regulator that has gain equal to the reciprocal of the modulator gain at desired crossover frequency and phase margin.
First two steps are input steps and the last step is output step i.e. easily achieved by the smartctrl feature of powersim simulator.
Type-3 regulator has two zero and three poles results in an additional phase boost of up to 90° more than type 2 can achieve which allows for higher loop cross-over frequency than type 2. Fig.4 shows the implementation of Type-3 regulator, Current Transfer function of Type-3 Regulator is given in “Equation. (10)”. Table II shows the design specification of Type-3 Regulator.

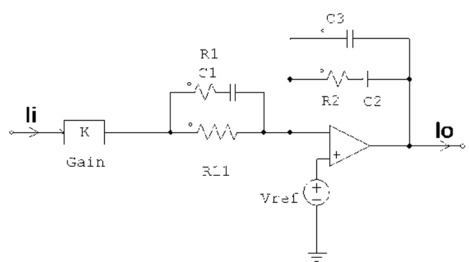
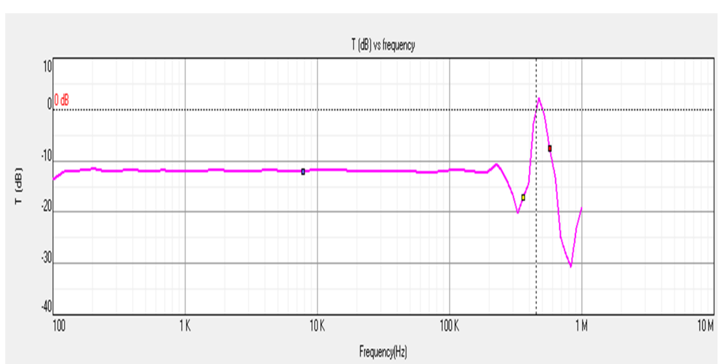


Fig.4 Implementation of Type-3 Regulator

$$\frac{I_o}{I_i} = \frac{K}{s.R_{11}.(C_1+C_2)} \cdot \frac{(1+s.C_2.R_2)}{(1+s.R_2.\frac{C_3.C_2}{C_3+C_2})} \cdot \frac{(1+s.C_1.(R_{11}+R_1))}{(1+s.C_1.R_1)} \quad (10)$$

TABLE II. DESIGN SPECIFICATION OF TYPE-3 REGULATOR

R_1	17KΩ/0.25W
R_2	585Ω/0.25W
R_{11}	10kΩ/0.25W
C_1	16pF
C_2	758pF
C_3	1.2Nf
G_{mod}	0.05
V_{ref}	2V
Gain(K)	120Ω
Switching Frequency	450Khz



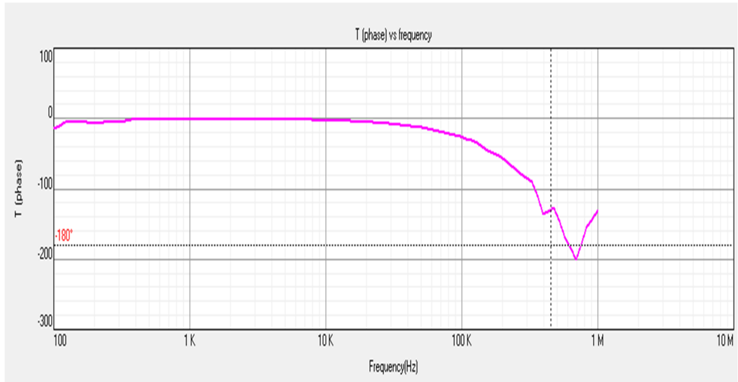


Fig.5 Bode Plot of open loop transfer function of Electric Control System

B. Stability Analysis

The Bode Plot of Electric Control System with Regulator or open loop transfer function of Electric Control System is shown in Fig.5. One can note that the system is stable, with a gain crossover frequency equal to 425 KHz, phase margin around 50° and gain margin around 40dB. Also performance of electric control system is significantly improved in terms of power variation. Now lamp power variation is 6% when load resistance is double due to aging but in case of open loop or Electric Control System without regulator the same lamp power variation is 25%.

V. Circuit Simulation And Simulation Results

PSIM simulation software tool is used to simulate the designed electric control system. Fig (6) shows the simulated circuit diagram of the electric control system along with Type 3 regulator. The simulation is done in two stages. In first stage the lamp equivalent load is run as a very high resistive voltage as MH lamp

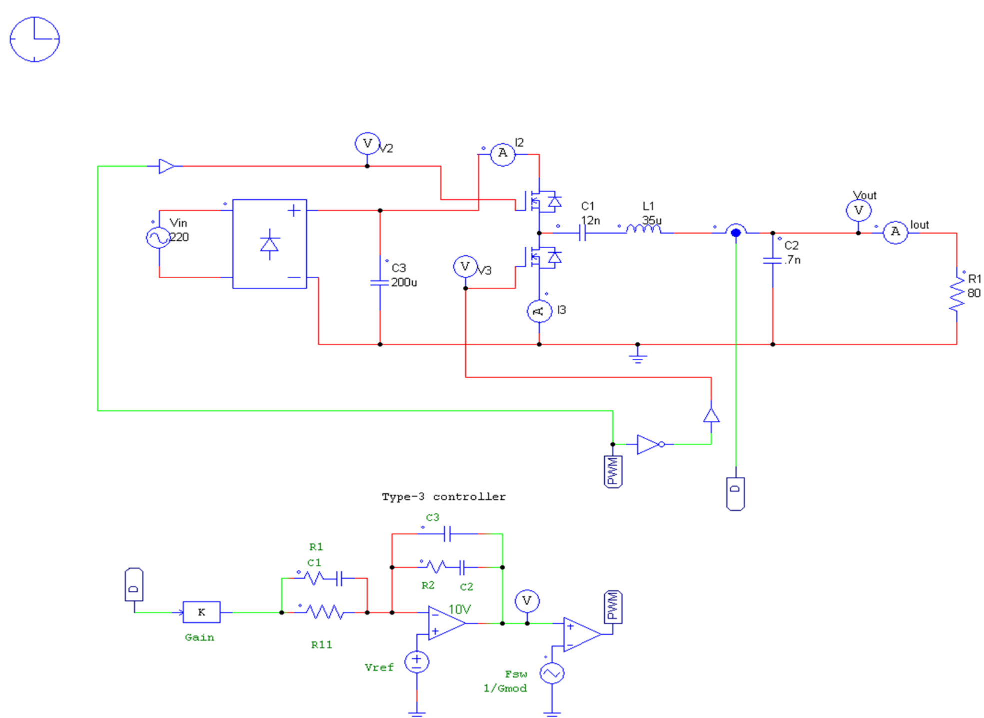


Fig.6 Simulated Circuit Diagram

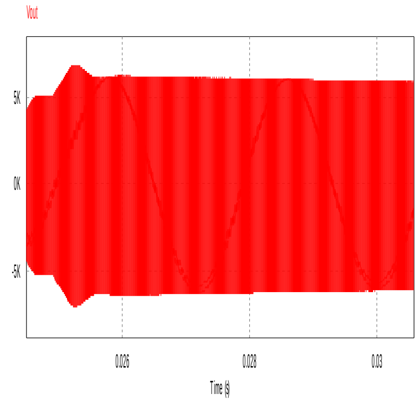
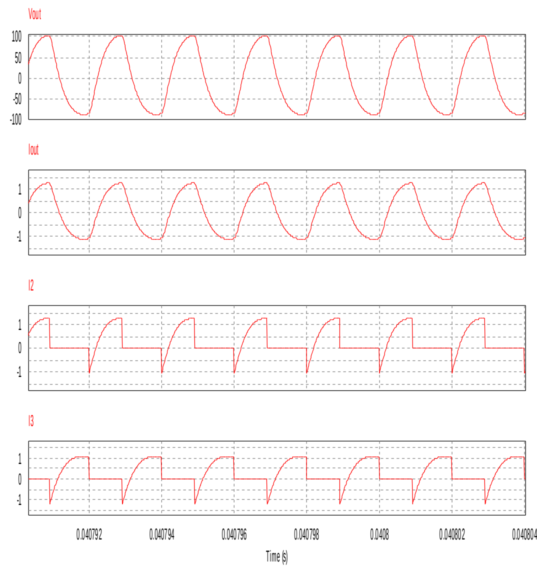


Fig.7 Lamp Voltage during starting



. Fig.8 Waveforms of lamp voltage and current along with switches current during normal running condition

behaves as an open circuit in ignition state. During normal running condition the lamp resistance is added as 80 ohm value, as discussed in the previous section. Fig (7) shows the simulation results of the ignition voltage across lamp. It is exactly as per the desired value.

Fig (8) is the simulation result of lamp voltage, lamp current and the current across both the switches. These results are as per expectations.

Table III is the summary of the stress of components during normal operating condition. This summary may be helpful to choose the components of the appropriate rating.

Table IV is the summary table of power variation of MH lamp with and without close loop.

TABLE III :COMPONENT STRESS: NORMAL OPERATION

Component	Voltage(Volt)	Current(Amp)
Inductor(L_s)	106	0.93
Capacitor(C_s)	82	0.93
Capacitor(C_p)	72	0.162
MOSFET(S_1)	176	0.65
MOSFET(S_2)	127	0.66

TABLE IV: SIMULATION RESULTS

Configuration	Power @ 80Ω load	Power @ 160Ω load	%Variation
Open Loop	77W	60W	25%
Close Loop	65W	61W	6%

The results of Table IV shows that the variation in lamp power with close loop control is under control as compared to open loop control.

VI. CONCLUSION

This paper presents a closed current loop solution for a constant power electric control system to supply 60W M.H lamp. A complete topology modelling was shown and confirmed in simulation. A reliable ignition method is proposed considering the frequency sweeping technique in the LC_sC_p circuit. The bode plots shows the frequency response as well as stability consideration at open loop and close loop configuration. The simulation results show that the system can be ignited reliably. The lamp power can be kept constant with in the safe limits.

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